

TITLE

Air-Pulse Generating Device with Asymmetric Initial Deflection

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63/744,882, filed on January 14th, 2025. The content of the application is incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] 1. FIELD OF THE INVENTION

[0003] The present application relates to an air-pulse generating device, and more particularly, to an air-pulse generating device capable of exploiting resonance gain.

[0004] 2. DESCRIPTION OF THE PRIOR ART

[0005] Unless otherwise indicated herein, the approaches described in this section are not prior art to the claims in this application and are not admitted as prior art by inclusion in this section.

[0006] Conventionally, speaker driver and back enclosure are two major design challenges in the speaker industry. It is difficult for one single conventional speaker (such as dynamic driver) to cover an entire audio frequency band, e.g., from 20 Hz to 20 KHz. To produce high fidelity sound with high enough sound pressure level (SPL), both the radiating/moving surface and volume/size of back enclosure for the conventional speaker are required to be sufficiently large.

[0007] US Patent No. 9,736,595 and No. 10,367,430 have discussed ultrasonic pulse for sound producing application has been discussed. Moreover, Applicant discloses APG (APG: air-pulse generating) device or APPS (APPS: air pressure pulse speaker), in US Patent No. 10,425,732, No. 11,172,310, No. 10,425,732, No. 11,043,197 and No. 11,445,279, to resolve the above bandwidth and size issues.

[0008] However, previously proposed APG devices have not fully utilize structural/device resonance gain, such that acoustic performance (such as SPL) is limited and it consumes more power.

[0009] Therefore, it is necessary to improve the prior art.

SUMMARY OF THE INVENTION

[0010] It is therefore a primary objective of the present application to provide an air-pulse generating device capable of exploiting resonance gain, to improve over disadvantages of the prior art.

[0011] An embodiment of the present application discloses an air-pulse generating device, comprising a film structure comprising a flap pair, wherein the flap pair comprises a first flap and a second flap opposite to each other; wherein the flap pair operates at an ultrasonic frequency, such that the air-pulse generating device produces a plurality of air pulses at an ultrasonic pulse rate; wherein the flap pair possesses an initial deflection difference or exhibits an average displacement difference between the first flap and the second flap (during an operation of the air-pulse generating device).

[0012] An embodiment of the present application discloses an air-pulse generating device, comprising a film structure comprising a flap pair, wherein the flap pair comprises a first flap and a second flap opposite to each other; wherein the flap pair operates at an ultrasonic frequency, such that the air-pulse generating device produces a plurality of air pulses at an ultrasonic pulse rate; wherein the flap pair performs a differential mode movement to form a virtual valve; wherein the virtual valve is closed during a time corresponding to a first reversal of a first flap movement of the first flap and a second reversal of a second flap movement of the second flap.

[0013] An embodiment of the present application discloses an air-pulse generating device, comprising a film structure comprising a flap pair, wherein the flap pair comprises a first flap and a second flap opposite to each other; wherein the flap pair operates at an ultrasonic frequency, such that the air-pulse generating device produces a plurality of air pulses at an ultrasonic pulse rate; wherein the flap pair performs a differential mode movement to form a virtual valve; wherein the flap pair performs a common mode movement, to form an ultrasonic pressure variation; wherein a pressure variant frequency corresponds to the common mode movement and a valve driving frequency corresponds to the differential mode movement are the same.

[0014] An embodiment of the present application discloses an air-pulse generating method, applied for an air-pulse generating device, the method comprising imposing an initial deflection difference or an average displacement difference between the first flap and the second flap;

wherein the air-pulse generating device comprises a flap pair, the flap pair comprises a first flap and a second flap opposite to each other; wherein the flap pair operates at an ultrasonic frequency, such that the air-pulse generating device produces a plurality of air pulses at an ultrasonic pulse rate.

[0015] These and other objectives of the present invention will no doubt become obvious to those of ordinary skill in the art after reading the following detailed description of the preferred embodiment that is illustrated in the various figures and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 is a side-view schematic diagram of an air-pulse generating device according to an embodiment of the present application.

[0017] FIG. 2 is a schematic diagram of signal waveforms according to an embodiment of the present application.

[0018] FIG. 3 is a schematic diagram of snapshots of membrane/flap movement according to an embodiment of the present application.

[0019] FIG. 4 is a schematic diagram of a frequency response of flap/membrane displacement according to an embodiment of the present application.

[0020] FIG. 5 is a side-view schematic diagram of an air-pulse generating device according to an embodiment of the present application.

[0021] FIG. 6 illustrates the relationship between flap displacement and valve opening according to an embodiment of the present application.

[0022] FIG. 7 illustrates the relationship between flap displacement and valve opening according to an embodiment of the present application.

[0023] FIG. 8 is a schematic diagram of signal waveforms according to an embodiment of the present application.

[0024] FIG. 9 is a schematic diagram of snapshots of membrane/flap movement according to an embodiment of the present application.

[0025] FIG. 10 is a side-view schematic diagram of air-pulse generating devices according to embodiments of the present application.

[0026] FIG. 11 is a side-view schematic diagram of an air-pulse generating device according to an embodiment of the present application.

[0027] FIG. 12 is a side-view schematic diagram of an air-pulse generating device according to an embodiment of the present application.

[0028] FIG. 13 is a top-view schematic diagram of an air-pulse generating device according to an embodiment of the present application.

DETAILED DESCRIPTION

[0029] Content of US Patent No. 11,943,585, Application No. 19/035,763 is incorporated herein by reference.

[0030] No. 11,943,585 filed by Applicant discloses an air-pulse generating (APG) device 10, which is shown in FIG. 1. The APG device 10 comprises a film structure 12 comprising a flap pair 102. The flap pair 102 comprises flaps 101 and 103 opposite to each other. The APG device 10 also comprises an actuator 101A disposed on the flap 101 and an actuator 103A disposed on the flap 103. The actuators 101A and 103A are driven by valve (demodulation) driving signals S101/SV1 and S103/SV2, respectively. The actuators 101A and 103A are also driven by a pressure (modulation) driving signal SM. Driven by the signals S101/SV1, S103/SV2 and SM, the APG device 10 is able to produce a plurality of air pulses at an ultrasonic pulse rate. The actuator 101A/103A comprises a top electrode and a bottom electrode. The two electrodes receive the valve (demodulation) driving signal and the pressure (modulation) driving signal. In the embodiment shown in FIG. 1, the top electrode receives the valve (demodulation) driving signal (e.g., S101/SV1 or S103/SV2) and the bottom electrode receives the pressure (modulation) driving signal SM, but not limited thereto.

[0031] The pressure (modulation) driving signal SM drives the flap pair 102 to perform a common mode movement, to form an ultrasonic air pressure variation. The valve (demodulation) driving signals S101 and S103 drive the flap pair to perform a differential mode movement. Suppose $U_{z,101}$ and $U_{z,103}$ represent displacement (in Z/vertical direction) of the flaps 101 and 103, respectively. The common mode movement may refer to a movement component of the flap pair which is $(U_{z,101} + U_{z,103})/2$, and the differential mode movement may refer to a movement component of the flap pair which is $|U_{z,101} - U_{z,103}|/2$.

[0032] A slit 112 is formed between the flaps 101 and 103. When the flap pair performs the differential mode movement (sometimes abbreviated as differential movement) such that $\Delta U_z = |U_{z,101} - U_{z,103}|$ is greater than a thickness of the flap, an opening (also denoted as 112) is formed. From one perspective, the differential movement of flaps 101 and 103 forms a virtual valve, also denoted as 112. When ΔU_z is small (smaller than the thickness of the flap) and/or an acoustic impedance/resistance is large so that airflow through the virtual valve 112 is negligible, the virtual valve 112 can be viewed as functionally closed. In this state, the virtual valve 112 retains a configuration of the slit 112, as shown in FIG. 1(a). When ΔU_z is large (larger than the thickness

of the flap) and/or an acoustic impedance/resistance is small so that airflow through the virtual valve 112 is significant, the virtual valve 112 can be viewed as functionally opened. In this state, the virtual valve 112 retains a configuration of the opening 112, as shown in FIG. 1(b).

[0033] FIG. 2(a) illustrates a driving scheme 20 showing waveforms of the signals S101/SV1, S103/SV2 and SM over multiple cycles T_{CY} . FIG. 2(b) illustrates waveforms of the signals S101/SV1, S103/SV2 and corresponding displacement $U_{z,101}/U_{z,103}$. FIG. 3 illustrates snapshots of membrane/flap movement for the flaps 101 and 103 using the driving scheme 20.

[0034] The pressure (modulation) driving signal SM driving the flap pair to perform the common mode movement is to produce an (amplitude-modulated) ultrasonic air pressure variation with an ultrasonic carrier frequency. The actual waveform of the pressure (modulation) driving signal SM is similar to a double sideband with suppressed carrier (DSB-SC) modulated signal (or can be viewed as a generalized DSB-SC modulated signal), which can be referred to US Patent No. 12,107,546 filed by Applicant, which is not narrated herein for brevity.

[0035] In the present application, S101/S103 represents (valve) driving signal for the “flap 101/103”, and SV1/SV2 represents first/second “valve” driving signal. Both S101 and SV1 are used to denote driving signal applied on the flap 101 to perform the differential movement. Similarly, both S103 and SV2 are used to denote driving signal applied on the flap 101 to perform the differential movement. $U_{z,101}$ and $U_{z,103}$ are used to denote displacement of the flaps 101 and 103, respectively.

[0036] In FIG. 2 and FIG. 3, under the driving scheme 20, at T_{11} and T_{13} , corresponding swinging transition times of flaps 101 and 103, the virtual valve 112 is closed; at T_{12} and T_{14} , corresponding reversal times of flaps 101 and 103, the virtual valve 112 is opened.

[0037] Note that, in the driving scheme 20 shown in FIG. 2, the valve driving signals S101/SV1 and S103/SV2 are biased at the *same level* VB, and the flap pair may perform a differential movement with *symmetric* initial deflection. Initial deflection, from one (but not only one) perspective, may refer to a degree or an amount of flap deflection corresponding to the bias voltage (combining stress, when/for performing the differential movement). Since the valve driving signals S101/SV1 and S103/SV2 are biased at the same level VB, the initial deflection of the flap 101 and the initial deflection of the flap 103 should be the same, and in other words, symmetric, despite manufacturing process variations or impairments. From another perspective, initial deflection may

also refer to neutral (stable) or average position when/for performing the differential movement.

[0038] From another perspective, the driving scheme 20 shown in FIG. 2, the flaps 101 and 103 may have same/symmetric average displacement. Average displacement of the flap 101 and average displacement of the flap 103 are (substantially) the same. There is no/barely average displacement difference between the flap 101 and 103. Herein average displacement may be taken over one or integer multiple of valve driving cycle(s) or over sufficient long period (e.g., 100 or more valve driving cycles), where the valve driving cycle, denoted as $T_{CY,V}$, may be $T_{CY,V} = 1 / F_V$, and F_V denotes valve driving frequency (will be detailed later).

[0039] However, given MEMS fabricated APG devices are high-Q devices (devices with high Q-factor), due to $F_V = \frac{1}{2} \cdot F_M$ (will be detailed later), mechanical resonant gain of the flap pair has not fully utilized (since only one of F_V or F_M enjoys resonance gain but the other does not, will be detailed later) and thus efficiency and effectiveness of the APG device are not optimized, when the flap pair is driven by the scheme 20.

[0040] Specifically, when the flap pair performs the differential movement with symmetric initial deflection (e.g., under the driving scheme 20), the valve driving frequency (denoted as F_V) corresponds to the differential mode movement would be a half of the pressure variant frequency (denoted as F_M) corresponds to the common mode movement, i.e., $F_V = \frac{1}{2} \cdot F_M$, where the valve driving frequency F_V is a frequency of the valve driving signal and the pressure variant frequency F_M is the ultrasonic carrier frequency of the DSB-SC modulation. In this case, since $F_V = \frac{1}{2} \cdot F_M$, only one of F_V and F_M can be placed closed to the structural resonant/resonance frequency F_r to benefit from the resonant gain. The other actuation signal may be limited to a lower gain.

[0041] In an embodiment, the pressure variant frequency F_M would also be the ultrasonic pulse rate F_{pulse} of the APG device.

[0042] For example, FIG. 4 illustrates a frequency response of flap/membrane displacement. If the pressure variant frequency F_M is close to or at the resonant frequency, e.g., $F_M \approx F_r$ ($F_r = 100\text{kHz}$ as shown in Fig. 4), the large gain (e.g., 10~50 times) is realized for generating the ultrasonic pressure variation. However, because of the virtual valve is driven at $F_V = \frac{1}{2} \cdot F_M$ (which is around 50kHz in Fig. 4), way out of the resonance region. Consequently, the displacement gain for differential movement with symmetric initial deflection is quite limited, reaching a mere 1.3 times, which is inefficient.

[0043] Note that, the displacement of the differential movement determines a degree of opening of the virtual valve 112. As taught in US Patent No. 11,943,585 and Application No. 19/287,761, the degree of opening of the virtual valve 112 determines demodulation conductance, which determines output performance such as sound pressure level (SPL), in sound producing application of the APG device.

[0044] Hence, limited displacement gain for differential movement with symmetric initial deflection would limit acoustic output performance such as SPL. Furthermore, to achieve a certain SPL, differential movement with symmetric initial deflection requires more/higher SV amplitude, amplitude of the valve driving signal (e.g., S101/SV1), and hence it would consume more power.

[0045] In addition, the differential movement with symmetric initial deflection would have false demodulation issue. It is because fabrication imperfections may result in an asymmetry between the opposing flaps 101 and 103. This may create a small demodulation carrier signal (acoustically) at F_V causing ultrasonic pulses around F_M to be demodulated not only around F_V , but also to the desired audible baseband. This may interfere with the quality of audio generation or may generate annoying audible tones for airflow devices if the demodulated acoustic signal falls within the audible range.

[0046] One remedy of such issues (e.g., driving inefficiency, false demodulation) is to impose Asymmetric initial deflection especially for the differential movement. In the following paragraphs, unless otherwise specified, discussion of flap displacement refers to (performing) differential movement, while common mode movement is ignored or assumed to be zero just for simplifying discussion of initial deflection.

[0047] FIG. 5 illustrates a schematic diagram of Asymmetric initial deflection imposed on an APG device 30 according to an embodiment of the present invention. The APG device 30 is similar to the APG device 10, especially in static membrane structure. Difference of the APG device 30 (or the APG devices of the present invention) versus the APG device 10 is the driving scheme or the dynamic membrane movement. Some notations of the APG device 10 may be retained for the APG device 30 (or the APG devices of the present invention).

[0048] For example, the APG device 30 comprises a film structure 12 comprising a flap pair 102, wherein the flap pair 102 comprises the flaps 101 and 103 opposite to each other. The flap

pair 102 operates at an ultrasonic frequency, such that the APG device 30 produces a plurality of air pulses at an ultrasonic pulse rate. The flap pair 102 performs a differential mode movement, to form virtual valve 112 or opening 112 at an opening frequency.

[0049] Different from the APG device 10, the flap pair 102 of the APG device 30 (or the APG devices of the present invention) possesses an initial deflection difference or exhibits an average displacement difference between the flap 101 and the flap 102, during an operation of the APG device.

[0050] In the embodiment shown in FIG. 5, the flap 101 is actuated to bend toward +Z direction (upward) and the flap 103 is actuated to bend toward -Z direction (downward). Different from the driving scheme 20, when the APG device 30 is imposed asymmetric initial deflection, the flap 101 initially deflects at an initial position $\phi_{0,101}$ and the flap 103 initially deflects at an initial position $\phi_{0,103}$, when/for performing the differential mode movement. An initial deflection difference or an average displacement difference exists between the flap 101 and the flap 103, where both initial deflection difference and average displacement difference are larger than a thickness of the film structure.

[0051] Furthermore, the flap 101 swings over a range RG1 between positions $\phi_{\min,101}$ and $\phi_{\max,101}$, expressed as $RG1 = [\phi_{\min,101}, \phi_{\max,101}]$, and the flap 103 swings over a range RG2 between positions $\phi_{\min,103}$ and $\phi_{\max,103}$, expressed as $RG2 = [\phi_{\min,103}, \phi_{\max,103}]$. Herein, $\phi_{\cdot, x}$ may be considered as (angular) position of tip of flap x with respect to its anchor.

[0052] When the flap 101 swings to position $\phi_{\min,101}$ and the flap 103 swings to position $\phi_{\max,103}$, the virtual valve 112 is considered as closed. In one embodiment, position $\phi_{\min,101}$ and position $\phi_{\max,103}$ may align with a certain horizontal level LV shown in FIG. 5. Swing range RG1 of the flap 101 is (substantially) above the level LV and swing range RG2 of the flap 103 is (substantially) below the level LV.

[0053] The transient displacements of flaps 101 and 103 and the resulting valve opening are shown in FIG. 6 (for symmetric deflection) and FIG. 7 (for Asymmetric deflection). In lower portion of FIG. 6 and FIG. 7, “opening being zero” means virtual valve 112 is closed.

[0054] For symmetric deflection, as shown in FIG. 6, the virtual valve 112 is closed during a period $T_{c,sym}$ within transition period of one flap swinging downward and the other flap swinging

upward. For Asymmetric deflection, on the other hand, the virtual valve 112 is closed during a period $T_{c,asm}$ when both flaps 101 and 103 are around/at their reversal/turning/extreme points, as shown in FIG. 7.

[0055] An advantage of Asymmetric deflection, where the virtual valve 112 is closed at the reversal/turning/extreme points of the two flaps, is the virtual valve 112 is closed only ONCE during one valve driving cycle $T_{CY,v}$, which makes “ $F_v = F_M$ and fully utilizing resonance gain” feasible.

[0056] Specifically, within one valve driving cycle $T_{CY,v,sym}$ for symmetric deflection, as shown in FIG. 6, the virtual valve 112 is closed twice: one is when the flap 101/103 swings downward/upward and the other is when the flap 101/103 swings upward/downward, which leads to $F_v = \frac{1}{2} \cdot F_M$. On the other hand, for Asymmetric deflection of the present invention, since the virtual valve 112 is always closed around/at the reversal/turning/extreme points, the virtual valve 112 is closed *only once* within/during one valve driving cycle $T_{CY,v,asm}$, as shown in FIG. 7, which makes “ $F_v = F_M$ and fully utilizing resonance gain” feasible.

[0057] Specifically, since $F_v = F_M$, the valve driving frequency F_v and the pressure variant frequency F_M are the same, both F_v and F_M may be located close to or at the resonance frequency F_r , so that large resonance gain may benefit the enlargement of both ultrasonic pressure variation and valve opening. In other words, since $F_v = F_M \approx F_r$, mechanical resonance gain can enlarge amplitude of both air pressure wave $P(t)$ and virtual valve conductance $G(t)$ shown in FIG. 4 of Application No. 19/287,761. Moreover, since large resonance gain can be utilized, only small amplitude of electrical signal is sufficient for producing significant SPL. Therefore, the scheme within $F_v = F_M \approx F_r$ would not only significantly improve acoustic output performance such as SPL of the APG device, over Patent No. 11,943,585, but also reduce power consumption for differential movement.

[0058] In the present invention, the valve driving frequency F_v or the pressure variant frequency F_M approaches the resonance frequency F_r , i.e., F_v or $F_M \approx F_r$, means that the valve driving frequency F_v or the pressure variant frequency F_M is so close to the resonance frequency F_r such that a certain displacement gain brought from resonance (or equivalently, resonance gain) is gained/obtained. Take FIG. 4 as an example, suppose vertical axis of FIG. 4 is in linear scale, F_v or $F_M \approx F_r$ may refer that the valve driving frequency F_v or the pressure variant frequency F_M is so close to the resonance frequency F_r such that a certain displacement/resonance gain (e.g., 10

times) is obtained. If the desired resonance gain is achieved as 10 times, then F_V or F_M in a range of (95KHz, 105KHz) may be considered as F_V or $F_M \approx F_r$. Practically/usually, resonance gain of 20~30 times (or above) is pursued, but not limited thereto.

[0059] In addition to resonance gain, the valve opening can be enlarged due to difference of initial deflection between the two flaps. For example, an maximum valve opening can be estimated as $opening = |d_{0,101} + d_{amp+,101} - (d_{0,103} - d_{amp-,103})|$ (eq. 1), where $d_{0,101}$, $d_{0,103}$ represent displacements corresponding to the initial position $\phi_{0,101}$, $\phi_{0,103}$, respectively, $d_{amp+,101}$ represents amplitude of differential mode oscillating displacement with respect to initial displacement $d_{0,101}$ toward +Z direction, and $d_{amp-,103}$ represents amplitude of differential mode oscillating displacement with respect to initial displacement $d_{0,103}$ toward -Z direction.

[0060] Eq. 1 can be rewritten as $opening = |d_{0,101} - d_{0,103}| + |d_{amp+,101} + d_{amp-,103}|$ (eq. 2). For symmetric deflection, $|d_{0,101} - d_{0,103}| = 0$ and $opening^{(sym)} = |d_{amp+,101} + d_{amp-,103}|$. For Asymmetric deflection, $|d_{0,101} - d_{0,103}| > 0$ and $opening^{(asm)} = |d_{0,101} - d_{0,103}| + |d_{amp+,101} + d_{amp-,103}| > opening^{(sym)}$. Therefore, the scheme of Asymmetric deflection and/or the scheme of virtual valve being closed at reversal points would significantly improve acoustic output performance such as SPL of the APG device, over Patent No. 11,943,585,.

[0061] The scheme of Asymmetric deflection can be realized by driving the two flaps 101 and 103 by two distinct valve driving signals which are biased at different bias level.

[0062] For example, FIG. 8(a) illustrates a driving scheme 30 showing waveforms of the signals S101/SV1, S103/SV2 and SM over multiple cycles T_{CY} , FIG. 8(b) illustrates waveforms of the signals S101/SV1, S103/SV2 and corresponding displacement $U_{z,101}/U_{z,103}$, and FIG. 9 illustrates snapshots of membrane/flap movement for the flaps 101 and 103 using the driving scheme 30.

[0063] As shown in FIG. 8, the valve driving signals S101/SV1 and S103/SV2 are biased at distinct levels (or bias voltages) VB1 and VB2. Hence, the initial deflection of the flap 101 and the initial deflection of the flap 103 are quite different. Moreover, when minimum of displacement (position of flap tip in Z axis) of flap 101 meets maximum of displacement (position of flap tip in Z axis) of flap 103, the valve may be closed only once within one valve driving cycle $T_{CY,v}$, which makes $F_V = F_M$ feasible.

[0064] Also, at time T_{22} , the valve driving signal S101/SV1 has negative polarity with respect

to the bias voltage VB1 and the valve driving signal S103/SV2 has positive polarity with respect to the bias voltage VB2, such that displacements $U_{z,101}$ and $U_{z,103}$ would achieve at level LV at the time T_{22} .

[0065] In other words, in FIG. 8 and FIG. 9, under the driving scheme 20, at times T_{21} and T_{23} , corresponding swinging transition times of flaps 101 and 103, the virtual valve 112 is opened; at time T_{22} , corresponding reversal times of flaps 101 and 103, the virtual valve 112 is closed.

[0066] Wiring of the pressure (modulation) driving signal SM to the flaps 101 and 103 may be seen/referred in FIG. 1, which is not narrated herein for brevity.

[0067] In addition to asymmetric bias voltage, fabrication processes may be used to establish the Asymmetric initial deflection.

[0068] As fabrication processes may be performed on entire substrates, opposite flaps may have similar layer stacks and are expected to have similar initial deflections. It may be beneficial when generating the Asymmetric initial deflection not to cause a large difference in resonant frequency, mass, or stiffness, as the dynamic modes discussed above may become unbalanced. Several methods may be used to controllably define the asymmetric initial deflection.

[0069] For example, the asymmetric initial deflection may be created by depositing layers with high internal mechanical stresses, and controlling the relative thickness of the high stress layers on the flap. In an embodiment (shown in FIG. 10), a controlled/first stress layer 111 (such as silicon oxide or nitride), may be deposited on/with one of the flaps 101 by various techniques such as chemical vapor deposition or sputtering, and patterned by masking or etching. Another layer with a *different stress* (or another/second stress layer) 113 may also be deposited and patterned on/with the other flap 103. In other words, a first internal stress of the first stress layer 111 is different from a second internal stress of the second stress layer 113. These stress layers 111 and 113 may be deposited over the piezoelectric layer 120 (as shown in FIG. 10(a)) or under the piezoelectric layer (FIG. 10(b)), where FIG. 10(a)/10(b) illustrates an APG device 50a/50b according to an embodiment of the present invention.

[0070] In another embodiment, localized heavy doping of silicon may be used to create regions of high stresses, as shown in FIG. 11, where an APG device 60 as an embodiment of the present invention is illustrated. Common dopants for silicon such as boron, phosphorus, or germanium are

known to introduce significant stresses into the silicon lattice at high concentrations, such as around 10^{20} atoms/cm³. These stresses may be compressive or tensile depending on the dopant. For example, at least one of the flaps 101 or 103 may have such heavy doping introduced into the silicon regions (doping region) 115 or 117 to obtain the desired stress.

[0071] In other words, a first doping characteristic of the first doping region 115 is different from a second doping characteristic of the second doping region 117. These doping characteristics may include, but are not limited to: (1) the dopant species or type (e.g., selecting distinct elements such as boron, phosphorus, or germanium to introduce specific lattice strains); (2) the doping concentration (e.g., utilizing different concentration levels, such as a heavy doping level of approximately 10^{20} atoms/cm³ versus a lighter doping level of 10^{15} atoms/cm³; and (3) the doping profile (e.g., the specific depth, gradient, or spatial distribution of the dopants within the flap). By configuring the first doping region 115 and the second doping region 117 to possess distinct doping characteristics, the magnitude and type (compressive or tensile) of the internal stresses can be individually tailored to achieve the desired asymmetric initial deflection.

[0072] In addition, a resonance chamber may be incorporated into the APG device of the present invention, like US Patent No. 12,413,900. For example, FIG. 12 is a schematic diagram of an APG device 70 according to an embodiment of the present invention. In addition to the flap pair, the APG device 70 further comprises a covering structure 203. A resonant chamber 201 is formed between the covering structure 203 and the film structure 12. Outlet(s) 202 and chamber walls 203 may be designed with an acoustic resonant frequency close to the structural resonance of the flap. A resonance may be formed within the resonant chamber 201. The resonance may be a Helmholtz resonance or a standing wave resonance, which is not limited thereto.

[0073] The purpose of the resonant chamber is to closely couple the structural common mode of the flaps with the acoustic environment. The resonant chamber 201 is designed to have an acoustic resonant frequency (such as a Helmholtz or half-wavelength mode) close to the structural common mode frequency of the flap pair. When operating near this coupled resonant frequency, the acoustic mode generates a high acoustic impedance region at the flap, which creates a substantial opposing force, consequently reducing the displacement and velocity of the common mode.

[0074] The reduction in common mode displacement means that the unwanted ultrasonic acoustic energy generated on the opposite side of the flaps (e.g., region 211) is reduced. This is

beneficial for saving wasted power and lowering the potential to cause annoyance or interfere with other ultrasonic device.

[0075] In addition, with smaller common-mode displacements, tooth-shaped flap edges as described in US Patent No. 12,317,034 are less likely to open at the teeth unintentionally or otherwise interfere with the valve operation due to nonlinearities. Smaller common-mode displacements make it less likely for tooth-shaped flap edges to unintentionally open or interfere with valve operation due to nonlinearities.

[0076] The flaps within the APG device of the present invention may comprise tooth edge. Flaps with tooth edge are illustrated in FIG. 13, detailed in No. 12,317,034, and not narrated herein for brevity.

[0077] Despite the reduced physical movement of the flaps, the pressure inside the acoustic resonance chamber 201 remains high, allowing for substantial power transmission from the structural flaps to the acoustic environment.

[0078] The differential mode movement, which is used for valve operation, involves the flaps moving in opposite directions. The differential mode movement may be mostly self-contained and balanced, since the differential flap movement causes the air surrounding the flaps to be mostly pushed back-and-forth locally between the vicinity of the opposing/opposite flaps 101 and 103. This results in minimal external acoustic interaction and low dissipation. Hence the quality factor of this mode may be high and it may not be significantly affected by acoustics further from the immediate vicinity of the flaps.

[0079] Collectively, the resonant chamber leverages the structural properties—the differential mode (for the valve) is decoupled (allowing high resonant gain), while the common mode (for ultrasound generation) is coupled. The coupling is used specifically to suppress unwanted common mode structural displacement, leading to reduced power consumption and noise.

[0080] In summary, the present invention provides an APG device with Asymmetric initial deflection. By imposing the asymmetric initial deflection, the device of the present invention enables the synchronization of valve driving and pressure modulation frequencies approaching the structural resonance ($F_V = F_M \approx F_r$). This alignment fully exploits the mechanical resonance to maximize displacement gain and valve conductance, significantly enhancing SPL and reducing

power consumption. The asymmetric initial deflection scheme also renders the device immune from false demodulation.

[0081] The foregoing outlines the features of several embodiments, enabling those skilled in the art to fully appreciate the aspects of the present disclosure. Those skilled in the art should recognize that the present disclosure provides a foundation for designing or modifying other processes and structures to achieve substantially the same functions and/or substantially the same results as those of the embodiments introduced herein. Furthermore, such equivalent arrangements do not deviate from the spirit and scope of the present disclosure, and various changes, substitutions, and alterations may be made without so departing.

CLAIMS

What is claimed is:

1. An air-pulse generating device, comprising:
a film structure comprising a flap pair, wherein the flap pair comprises a first flap and a second flap opposite to each other;
wherein the flap pair operates at an ultrasonic frequency, such that the air-pulse generating device produces a plurality of air pulses at an ultrasonic pulse rate;
wherein the flap pair possesses an initial deflection difference or exhibits an average displacement difference between the first flap and the second flap.
2. The air-pulse generating device of claim 1,
wherein the initial deflection difference is larger than a thickness of the film structure.
3. The air-pulse generating device of claim 1,
wherein a first average displacement corresponding to the first flap is different from a second average displacement corresponding to the second flap;
wherein a difference between the first average displacement and the second average displacement is larger than a thickness of the film structure.
4. The air-pulse generating device of claim 1,
wherein the flap pair performs a differential mode movement, to form a virtual valve or an opening at an opening frequency.
5. The air-pulse generating device of claim 4,
wherein the flap pair is driven according to a valve driving frequency to perform the differential mode movement;
wherein the valve driving frequency is the ultrasonic pulse rate.
6. The air-pulse generating device of claim 4,
wherein the flap pair performs a common mode movement, to form an ultrasonic air pressure variation.
7. The air-pulse generating device of claim 6,
wherein a pressure variant frequency corresponds to the common mode movement and a valve driving frequency corresponds to the differential mode movement are the same.

8. The air-pulse generating device of claim 7,
wherein both the pressure variant frequency and the valve driving frequency approach a
resonance frequency of the flap pair.
9. The air-pulse generating device of claim 1,
wherein the virtual valve is closed during a time corresponding to a first reversal of a first
flap movement of the first flap and a second reversal of a second flap movement of the
second flap.
10. The air-pulse generating device of claim 1,
wherein the first flap is actuated to bend toward a first direction while the second flap is
actuated to bend toward a second direction opposite to the first direction.
11. The air-pulse generating device of claim 1,
wherein the first flap is driven by a first valve driving signal and the second flap is driven
by a second valve driving signal, to form a virtual valve;
wherein the first valve driving signal comprises a first bias voltage and the second valve
driving signal comprises a second bias voltage;
wherein the first bias voltage is different from the second bias voltage.
12. The air-pulse generating device of claim 11,
wherein the first valve driving signal has a first polarity with respect to the first bias voltage
and the second valve driving signal has a second polarity with respect to the second
bias voltage;
wherein the first polarity and the second polarity are opposite to each other.
13. The air-pulse generating device of claim 11,
wherein the first flap and the second flap are driven by a pressure driving signal, to perform
a common mode movement to form a pressure variation.
14. The air-pulse generating device of claim 13,
wherein a valve driving frequency corresponding to the first valve driving signal and a
pressure variant frequency corresponding to the pressure driving signal are the same.

15. The air-pulse generating device of claim 13, comprising:
a first actuator disposed on the first flap and a second actuator disposed on the second flap.
16. The air-pulse generating device of claim 15,
wherein the first actuator comprises a first electrode and a second electrode, and the second actuator comprises a third electrode and a fourth electrode;
wherein the first electrode receives the first valve driving signal and the third electrode receives the second valve driving signal;
wherein the second electrode and the fourth electrode receive the pressure driving signal.
17. The air-pulse generating device of claim 1, comprising:
a first stress layer disposed with the first flap and a second stress layer disposed with the second flap;
wherein a first internal stress of the first stress layer is different from a second internal stress of the second stress layer.
18. The air-pulse generating device of claim 1, comprising:
wherein the first flap comprises a first doping region and the second flap comprises a second doping region;
wherein a first doping characteristic of the first doping region is different from a second doping characteristic of the second doping region.
19. The air-pulse generating device of claim 1, comprising:
a covering structure;
wherein a resonant chamber is formed between the covering structure and the film structure;
wherein a resonance is formed within the resonant chamber.
20. The air-pulse generating device of claim 19,
wherein the resonance is a Helmholtz resonance or a standing wave resonance.
21. The air-pulse generating device of claim 1,
wherein the first flap and the second flap comprise tooth edges.
22. An air-pulse generating device, comprising:
a film structure comprising a flap pair, wherein the flap pair comprises a first flap and a

second flap opposite to each other;
wherein the flap pair operates at an ultrasonic frequency, such that the air-pulse generating device produces a plurality of air pulses at an ultrasonic pulse rate;
wherein the flap pair performs a differential mode movement to form a virtual valve;
wherein the virtual valve is closed during a time corresponding to a first reversal of a first flap movement of the first flap and a second reversal of a second flap movement of the second flap.

23. An air-pulse generating device, comprising:

a film structure comprising a flap pair, wherein the flap pair comprises a first flap and a second flap opposite to each other;
wherein the flap pair operates at an ultrasonic frequency, such that the air-pulse generating device produces a plurality of air pulses at an ultrasonic pulse rate;
wherein the flap pair performs a differential mode movement to form a virtual valve;
wherein the flap pair performs a common mode movement, to form an ultrasonic pressure variation;
wherein a pressure variant frequency corresponds to the common mode movement and a valve driving frequency corresponds to the differential mode movement are the same.

24. An air-pulse generating method, applied for an air-pulse generating device, the method comprising:

imposing an initial deflection difference or an average displacement difference between the first flap and the second flap;
wherein the air-pulse generating device comprises a flap pair, the flap pair comprises a first flap and a second flap opposite to each other;
wherein the flap pair operates at an ultrasonic frequency, such that the air-pulse generating device produces a plurality of air pulses at an ultrasonic pulse rate.

25. The method of claim 24, wherein the step of imposing the initial deflection difference or the average displacement difference between the first flap and the second flap comprises:
driving the first flap by a first valve driving signal and driving the second flap by a second valve driving signal;
wherein the first valve driving signal comprises a first bias voltage and the second valve driving signal comprises a second bias voltage;
wherein the first bias voltage is different from the second bias voltage.

26. The method of claim 24, wherein the step of imposing the initial deflection difference or the average displacement difference between the first flap and the second flap comprises:
imposing a difference between a first layer stack corresponding to the first flap and a second layer stack corresponding to second first flap;
wherein a first deflection of the first flap is different from a second deflection of the second flap in response to a certain driving signal pattern.
27. The method of claim 24, wherein the step of imposing the initial deflection difference or the average displacement difference between the first flap and the second flap comprises:
forming a first stress layer on the first flap and forming a second stress layer on the second flap;
wherein the first stress layer and the second stress layer possess different stress in response to a certain driving signal pattern.
28. The method of claim 24, wherein the step of imposing the initial deflection difference or the average displacement difference between the first flap and the second flap comprises:
forming a first doping region within the first flap and a second doping region within the second flap;
wherein doping characteristics of the first doping region and the second doping region are different.